

# The origin of short-lived radionuclides and the astrophysical environment of solar system formation

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## ABSTRACT

Based on early solar system abundances of short-lived radionuclides (SRs), such as  $^{26}\text{Al}$  ( $T_{1/2} = 0.74$  Myr) and  $^{60}\text{Fe}$  ( $T_{1/2} = 1.5$  Myr), it is often asserted that the Sun was born in a large stellar cluster, where a massive star contaminated the protoplanetary disk with freshly nucleosynthesized isotopes from its supernova (SN) explosion. To account for the inferred initial solar system abundances of short-lived radionuclides, this supernova had to be close ( $\sim 0.3$  pc) to the young ( $\leq 1$  Myr) protoplanetary disk.

Here we show that massive star evolution timescales are too long, compared to typical timescales of star formation in embedded clusters, for them to explode as supernovae within the lifetimes of nearby disks. This is especially true in an Orion Nebular Cluster (ONC)-type of setting, where the most massive star will explode as a supernova  $\sim 5$  Myr after the onset of star formation, when nearby disks will have already suffered substantial photoevaporation and/or formed large planetesimals.

We quantify the probability for *any* protoplanetary disk to receive SRs from a nearby supernova at the level observed in the early solar system. Key constraints on our estimate are: (1) SRs have to be injected into a newly formed ( $\leq 1$  Myr) disk, (2) the disk has to survive UV photoevaporation, and (3) the protoplanetary disk must be situated in an enrichment zone permitting SR injection at the solar system level without disk disruption. The probability of protoplanetary disk contamination by a supernova ejecta is, in the most favorable case,  $3 \times 10^{-3}$ .

*Subject headings:* solar system: Origins, Sun: Short-lived radioactivities; Supernovae; Meteorites; ISM: individual (Carina Nebula), stars: formation

## 1. Introduction

Short-lived radionuclides (SRs) are radioactive elements with half-lives of the order of 1 Myr. Their presence in the nascent solar system is inferred from an excess of their daughter isotopes in meteorite components (Russell, Gounelle & Hutchison 2001). Some SRs [ $^{10}\text{Be}$  ( $T_{1/2} = 1.5$  Myr),  $^{26}\text{Al}$  ( $T_{1/2} = 0.74$  Myr),  $^{36}\text{Cl}$  ( $T_{1/2} = 0.30$  Myr),  $^{41}\text{Ca}$  ( $T_{1/2} = 0.10$  Myr),  $^{53}\text{Mn}$  ( $T_{1/2} = 3.7$  Myr),  $^{60}\text{Fe}$  ( $T_{1/2} = 1.5$  Myr)] were present in the protoplanetary disk at abundances substantially higher than the levels expected for average interstellar medium (Meyer & Clayton 2000). These SRs cannot therefore be inherited from the interstellar medium and require a last minute origin (e.g. Wadhwa et al. 2007). The origin of SRs is highly debated in the cosmochemistry community, because it has important consequences for e.g. early solar system chronology (e.g. McKeegan & Davis 2004; Gounelle & Russell 2005a,b) and planetesimal heating (Urey 1955; Ghosh & McSeen 1998). In addition, understanding the origin of SRs will provide key constraints on the astrophysical environment in which our solar system was born (e.g. Hester & Desch 2005; Goswami et al. 2005; Gounelle 2006).

Generally speaking, SRs can be made either by thermal nucleosynthesis, at KeV energies in the interior of stars, or by non-thermal nucleosynthesis, i.e. nuclear reactions involving cosmic rays or accelerated particles at MeV energy from the Sun. There are therefore two possible sources for short-lived radionuclides in the solar protoplanetary disk: (a) Injection into the molecular cloud core or protoplanetary disk from a nearby, late-type star (e.g. Busso, Gallino & Wasserburg 2003), (b) *In situ* production in the protoplanetary disk by irradiation of dust and gas with accelerated particles from the proto-Sun (e.g. Gounelle et al. 2006).

We focus here on the possible delivery of SRs by a late type star. Asymptotic Giant Branch (AGB) stars are possible candidates (Wasserburg et al. 2006), but this source of SRs in the early solar system is considered highly unlikely because of the low probability of an encounter between an AGB star and a star forming region (Kastner & Myers 1994). Type II supernovae represent an alternative to AGB stars as a source of SRs (Cameron et al. 1995).

Of models based on a supernova (SN) origin for SRs there are two types. Either a SN injects freshly synthesized SRs into a nearby molecular cloud core, triggering its gravitational collapse (Cameron & Truran 1977; Cameron et al. 1995; Boss & Vanhala 2000), or directly into a nearby protoplanetary disk (Chevalier 2000; Hester & Desch 2005; Ouellette et al. 2005). The first SN scenario is now considered less likely because only very specific conditions allow a supernova shockwave to trigger the collapse of a molecular cloud core and, at the same time, inject SRs (e.g. Boss & Vanhala 2000). In the second scenario, which is currently receiving a lot of attention (Chevalier 2000; Hester & Desch 2005; Ouellette et al. 2005; Ouellette, Desch & Hester 2007), the SN has to be very close ( $\sim 0.3$  pc) to the protoplanetary

disk in order to allow the disk to intercept enough SN ejecta to account for the solar system inventory of SRs. It is thus assumed that the massive star, which evolved into a SN, and the protoplanetary disk were coeval and formed in the same stellar cluster (e.g. Hester & Desch 2005). Massive stars form in large stellar clusters (Lada & Lada 2003). The nearby SN injection model therefore implies that our Sun was born in a large stellar cluster. The Orion Nebula Cluster (ONC) is often cited as a good analog for such an environment (Hester & Desch 2005).

However, if the Sun was born in a stellar cluster massive enough to contain a SN, it has important implications for the childhood of our solar system. Massive stars are known to power winds carving large bubbles of hot gas in surrounding cold molecular gas (Weaver et al. 1977). They also emit large UV fluxes, which create HII blisters in cold molecular gas (O’Dell 2001) and photoevaporate nearby protoplanetary disks (e.g. Johnstone, Bally & Hollenbach 1998). The presence of numerous massive stars close to planetary systems can also dynamically modify the orbits of the giant planets and of Kuiper Belt Objects (e.g. Adams & Laughlin 2001). It is therefore essential to evaluate the *a priori* probability of our Sun to be born in such an harsh astrophysical setting.

Adams & Laughlin (2001) estimated the probability of the Sun to have been born in a stellar environment large enough to contain a massive star (which could deliver SRs via a SN explosion) and small enough to preserve both the orbits of the giant planets as well as those of the Kuiper belt objects. These authors made the assumption that *any* star more massive than  $25 M_{\odot}$  was able to deliver SRs to the solar protoplanetary disk, and they did not place constraints on the time window during which SRs were injected into the disk. The spatial structure of the cluster was not included in this model. Subsequently, Williams & Gaidos (2007) provided an estimate for the probability of the nearby SN injection scenario. However this estimate did not take quantitatively into account the disk photoevaporation and overestimated the time window during which SN injection of SRs in a nearby protoplanetary disk can occur.

The present work is organized as follows. First, we review the cosmochemical constraints on the origin of SRs (§2). Second, we present recent observations and models of molecular cloud dynamics, star formation rate, accretion disk lifetime and evolutionary timescales of massive stars pertinent to an evaluation of the proposed ONC-like setting for the formation of the solar system (§3). Third, we calculate the probability for a protoplanetary disk attached to a low-mass star to receive SRs from a nearby SN at the levels inferred for the early solar system, with the necessary constraints that SR delivery happens within the time window specified by the cosmochemical data, and that the disk is not destroyed by UV photoevaporation (§4). Our model assumptions and limitations are discussed in section

§5. In section §6 we present the implications of our findings for the origin of short-lived radionuclides.

## 2. Polluting our protoplanetary disk with a SN ejecta: Timing and distance

Among the SRs that could have been delivered by a supernova to the protoplanetary disk around the young Sun,  $^{26}\text{Al}$  provides the strongest constraint on the timing of such an event (e.g. Wadhwa et al. 2007; Russell et al. 2006). Aluminium-26 is more abundant in primitive chondrite components, such as Calcium-, Aluminium-rich Inclusions (CAIs) and chondrules (e.g. Galy et al. 2000) than in more evolved asteroidal crustal rocks (e.g. Srinivasan et al. 1999). CAIs have the oldest measured Pb-Pb ages of any solid matter in the solar system (Bouvier et al. 2007). Some iron meteorites, believed to sample the cores of differentiated asteroids, have model Hf-W ages as old as those of CAIs (Markowski et al. 2006). They must therefore have formed contemporaneously with CAIs. This implies that  $^{26}\text{Al}$ , which is believed to have been the main heat source responsible for asteroidal differentiation, was present in the protoplanetary disk already at the time of iron meteorite parent-asteroid accretion (Bottke et al. 2006). Both observations suggest that  $^{26}\text{Al}$  was present in the protoplanetary disk from the early stages of its evolution, certainly as far back in time as the meteorite record can bring us (e.g. Wadhwa et al. 2007; Russell et al. 2006). Although the exact timescale is not known, it is reasonable to assume that if  $^{26}\text{Al}$  was delivered to the solar system from a SN source, this injection occurred during the class 0 or class I stage of our protoSun (e.g. Montmerle et al. 2006). The combined duration of the class 0 and class I phases is  $\sim 10^5$  yr. Here we will conservatively assume that the SN delivery of SRs to the protoplanetary disk occurred within a time interval,  $\Theta$ , of  $\sim 1$  Myr after the formation of the disk (see also Ouellette et al. 2005; Looney, Tobin & Fields 2006).

The distance  $r$  between the SN and the protoplanetary disk cannot be too small, otherwise the disk will be destroyed by the impact of the ejecta. Nor can this distance be too large because this would limit the amount of injected SRs. There is a restricted distance interval, the 'minimum' ( $r_{\min}$ ) and the 'maximum' ( $r_{\max}$ ) acceptable distance between the SN and protoplanetary disk, referred to as the 'enrichment zone', which satisfies these two important constraints.

Chevalier (2000) estimated that at distances smaller than 0.25 pc, momentum transfer between the SN ejecta and the disk will cause the later to be stripped away. Based on 2D numerical simulations, Ouellette, Desch & Hester (2007) concluded that a disk as close as 0.1 pc from a  $25 M_{\odot}$  SN can survive disruption. For the minimum distance,  $r_{\min}$ , we will adopt a conservative value of 0.1 pc.

The maximum distance  $r_{\max}$ , below which the protoplanetary disk receives enough SRs to account for solar system abundances depends on a limited number of parameters. Though it is beyond the scope of the present paper to explicitly derive  $r_{\max}$ , we indicate how it can be calculated and summarize the estimates given by several groups (Ouellette et al. 2005; Looney, Tobin & Fields 2006).

For any radionuclide, the mixing fraction,  $f$ , of the supernova ejecta mixed into the protoplanetary disk is:

$$f = \frac{M_{\text{SS}}}{\eta Y_{\text{SN}}} \times e^{\Delta/\tau}, \quad (1)$$

where  $M_{\text{SS}}$  is the initial mass of the radionuclide in the solar system (in  $M_{\odot}$ ),  $Y_{\text{SN}}$  is the total yield of the radionuclide from the considered supernova (in  $M_{\odot}$ ),  $\tau$  is the mean life,  $\eta$  the injection efficiency and  $\Delta$  is the time interval between the end of nucleosynthesis in the supernova and incorporation into refractory meteorite components (CAIs). Note that  $f \ll 1$  as  $M_{\text{SS}} \ll Y_{\text{SN}}$  and  $\Delta \approx \tau$  (see below). Following Cameron et al. (1995), we translate the mixing fraction  $f$  into a geometrical relationship,  $r = \frac{r_0}{2} \sqrt{1/f}$ , where  $r_0$  is the size of the disk and  $r$  the distance between the disk and the massive star. Putting these two expressions together, we obtain the general expression:

$$r = \frac{r_0}{2} \sqrt{\eta \frac{Y_{\text{SN}}}{M_{\text{SS}}} e^{-\Delta/\tau}}. \quad (2)$$

$M_{\text{SS}}$  is estimated from the disk mass, the solar abundances and the initial abundance of the considered radionuclide identified to that of CAIs (e.g. Gounelle & Meibom 2007). Using SN yields calculated by state-of-the art nucleosynthetic models corresponding to a large range of progenitor masses and metallicities (Rauscher et al. 2002; Woosley & Weaver 1995), and assuming an injection efficiency of 1, Looney, Tobin & Fields (2006) as well as Ouellette et al. (2005) calculate that the solar protoplanetary disk had to be at a distance between 0.02 and 0.3 pc from the massive star for disk sizes varying between 30 and 100 AU.  $\Delta$  is constrained by the decay of short-lived radionuclides and is of the order of  $\sim 1$  Myr. Note that the disk size cannot be significantly larger than 100 AU because, before any injection occurs, the disk has been sitting nearby a strongly ionizing O star for some Myr (see section 3), resulting in severe disk truncation (Ouellette et al. 2005). The alternative case of larger disks examined by Looney, Tobin & Fields (2006) is therefore not relevant here. For more realistic values of  $\eta$  (i.e.  $\eta \ll 1$ ) the injection distance is reduced to values approaching the minimum acceptable distance (0.1 pc), which would cause a problem with regard to disk survivability. We will consider here that a generous maximum distance between the protoplanetary disk and the supernova is  $r_{\max} = 0.4$  pc.

Therefore, the acceptable distance interval for which the SN explosion delivers SRs at

the level observed in the solar system, but does not destroy the protoplanetary disk is quite narrow. The enrichment zone lies therefore between  $r_{\min} = 0.1$  pc and  $r_{\max} = 0.4$  pc.

### 3. The unlikely ONC-like setting

The Orion Nebular Cluster is the epitome of a massive star forming region in the solar neighborhood, often invoked as an analog for the birthplace of our Sun (Hester & Desch 2005; Ouellette et al. 2005; Bally, Moeckel & Throop 2005). The ONC is dominated by the four bright Trapezium O and B stars, which are named  $\theta^1$  and numbered from A to D (O’Dell 2001). It is situated  $\sim 450$  pc away from the Sun and contains roughly half a dozen stars massive enough to end their lives as SN (Hillenbrand 1997). In the ONC, the most massive object is the O7 star  $\theta^1 C$  Ori, which has a mass of  $\sim 40 M_{\odot}$ . Within 1 pc of  $\theta^1 C$  Ori are thousands of low-mass protostars, 70% of which have disks (Hillenbrand et al. 1998). Some of the disks are as close as a few tenths of a parsec from  $\theta^1 C$  Ori.

Though evolving on substantially shorter timescales than low-mass stars, high mass stars still need a finite time to complete hydrogen and helium burning, and explode in a SN (Schaller et al. 1992; Romano et al. 2005). It takes  $\sim 40$  Myr for a  $8 M_{\odot}$  B3 star and  $\sim 3$  Myr for an extremely massive  $120 M_{\odot}$  O3 star to reach the SN stage respectively. A  $40 M_{\odot}$  star, such as  $\theta^1 C$  Ori, evolves for  $\sim 5$  Myr before it goes supernova (Figure 1).

The age of the ONC is estimated to be  $\leq 1$  Myr (e.g. Hillenbrand 1997). The age of  $\theta^1 C$  Ori is not precisely known, although this star is probably among the youngest members of the ONC, because early formation of  $\theta^1 C$  Ori would have halted star formation through rapid photoionization of the surrounding gas (O’Dell 2001; Boss & Goswami 2007). O’Dell (2001) argues that  $\theta^1 C$  Ori is *the* youngest star in the ONC cluster. Palla & Stalher (2001) determined the age of another Trapezium star,  $\theta^1 D$  Ori, and find an upper limit of 0.1 Myr. Here it is conservatively assumed that  $\theta^1 C$  Ori is 1 Myr old and will go SN 5 Myr after the onset of star formation in the ONC, i.e.  $\sim 4$  Myr from now.

The protoplanetary disks that are currently within a few tenths of a parsec from  $\theta^1 C$  Ori will suffer severe mass-loss due to photoevaporation driven by the UV radiation from this and other massive stars in the region (Johnstone, Hollenbach & Bally 1998; Störzer & Hollenbach 1999; Richling & Yoke 2000; Balog et al. 2007). Typical mass loss rates due to photoevaporation are  $10^{-7} M_{\odot}/\text{yr}$  (Johnstone, Hollenbach & Bally 1998; Störzer & Hollenbach 1999). The typical lifetime of a minimum mass solar nebula of mass  $0.01 M_{\odot}$  (Hayashi et al. 1985) in such an environment is therefore  $\sim 10^5$  yr. Johnstone, Hollenbach & Bally (1998) studied the specific case of  $\theta^1 C$  Ori and showed that, at a distance of 0.3 pc,

a protoplanetary disk would shrink to a size of about 1 AU in about 1 Myr, i.e. well before  $\theta^1 C$  Ori becomes a SN. Disk evaporation simply prevents injection of SN ejecta because disks in the vicinity of the SN have essentially disappeared before the SN explosion takes place.

It is possible that disks adjacent to  $\theta^1 C$  Ori could partially survive photo-evaporation if their orbits around the massive star are highly elliptical rather than circular (e.g. Adams & Bloch 2005), or if the photo-evaporation rate decreases rapidly with time (e.g. Adams et al. 2006). However, in 4 Myr from now, when  $\theta^1 C$  Ori goes supernova, such surviving disks will be highly evolved, harboring large planetesimals as well as giant planets (e.g. Montmerle et al. 2006). In an Orion-like setting, planetary formation is accelerated by photoevaporation (Throop & Bally 2005), reducing accordingly the time window for SR injection. Disks which survive evaporation will therefore not receive SRs from the SN explosion until very late in their evolution, inconsistent with cosmochemical evidence for early delivery, which indicates that the injection happened within 1 Myr of disk formation (see section 2).

Over the next 4 million years, there will be few new low-mass stars forming within 1 pc of  $\theta^1 C$  Ori. Star formation is certainly more vigorous during the first Myr of a molecular cloud lifetime and decreases sharply with time (see Lada & Lada 2003). After a few Myr, the gas in a molecular cloud has dissipated, and new star formation no longer takes place (Leisawitz, Bash & Thaddeus 1989; Elmegreen 2000; Hartmann, Ballesteros-Paredes & Bergin 2001; Lada & Lada 2003). Winds from massive stars and outflows from low-mass stars are primarily responsible for the quick dissipation of the molecular gas (Bally, Moeckel & Throop 2005). In fact, young clusters, such as NGC1333 and Serpens, contain relatively large populations of Class 0 sources and are rich in bipolar flows, both features indicative of the earliest stages of star formation (e.g. Knee & Sandell 2000; Sandell & Knee 2001). In contrast, older clusters, such as IC348, contain few protostellar sources and outflows (Lada & Lada 2003). The fraction of disks in a given cluster, which is homologous to the star formation rate, also steeply decreases with the cluster age (see Figure 1 of Haisch, Lada & Lada 2001).

The decrease with time of the star forming rate is even more dramatic in the immediate vicinity of a massive star ( $\lesssim$  few pc) than at the global molecular cloud scale. Hillenbrand (1997) argues that star formation in the Trapezium, i.e. in the vicinity of  $\theta^1 C$  Ori, is now over. More generally, star formation cannot occur in the absence of molecular gas, which is ionized by the enhanced UV flux of massive stars. Wren & O'Dell (1995) estimate that the ionized HII region created by  $\theta^1 C$  Ori is now 0.3 pc wide and is growing at the rate of 0.5 km/s. Within the next 4 Myr, this region will expand to a  $\sim 2.3$  pc wide HII cavity around  $\theta^1 C$  Ori, where star formation will be effectively halted. Hillenbrand & Hartmann (1998) estimate that the  $\sim 1$  pc wide gaseous region surrounding  $\theta^1 C$  Ori will be photoevaporated on a timescale of  $\leq 1$  Myr.

It is not only the ionizing power of massive stars, such as  $\theta^1 C$  Ori, that contributes to the sharp decrease in star formation rate in their immediate vicinity. The winds emanating from the massive stars create bubbles. The linear dimension of a wind bubble increases with the mass of the star (Chevalier 1999). A  $20 M_{\odot}$  star creates a cavity as large as 11 pc in 7 Myr (Chevalier 1999), suggesting that the molecular gas surrounding  $\theta^1 C$  Ori will be dissipated by winds in addition to photoionization on timescales significantly shorter than the lifetime of  $\theta^1 C$  Ori.

After a few Myr of evolution, star formation in ONC-like settings occurs mainly in photo-dissociation regions (PDRs) at the interface of the HII region and the molecular gas (Healy, Hester & Claussen 2004), a few parsecs away from the massive star. The fate of the ONC is well illustrated by the 2-3 Myr old NGC2244 cluster, whose most massive star, HD206267, has the same spectral type as  $\theta^1 C$  Ori. In NGC2244, star formation is occurring in the outskirts of the cluster, at distances 5-10 pc from the central O6 star (Hartmann 2005). In addition, Reach et al. (2004) note that these stars, which formed  $\sim 2$  Myr before HD206267 goes supernova, are the last generation of stars forming in the cluster. Low-mass stars formed 3 Myr after the onset of star formation in a given molecular cloud are too far away to be contaminated by SRs at any significant level.

Figure 2 illustrates the discrepancy between the timescales of massive star evolution and low-mass star formation for an ONC-like setting.

#### 4. Probability of SR injection in a young disk by a nearby SN

In this section, we calculate two numbers: (1) Within a cluster of a given size  $N_*$ , what is the probability for a young disk ( $\leq 1$  Myr) attached to a low-mass star to be contaminated in SRs by a nearby supernova explosion at the level observed in the early solar system? (2) What is the probability for *any* protoplanetary disk in the Galaxy to be contaminated in SRs from a nearby SN explosion at the level observed in the solar system? The latter number will be calculated by integrating the former with the cluster size distribution (section 4.6).

The probability for a disk surrounding a low-mass star in a cluster of a given size ( $N_*$ ) to be enriched in SRs by a nearby supernova at the observed solar system abundance without being disrupted by UV photoevaporation is given by the expression:

$$P_{\text{SR}}(N_*) = \int_{M_l}^{M_u} f_{\text{YSO}}(t_{\text{SN}}) f_{\text{enrichment}} f_{\text{survivors}} \mathcal{P}_{M_{\text{SN}}}(N_*) dM_{\text{SN}}, \quad (3)$$

where  $f_{\text{YSO}}$  is the fraction of young ( $\leq 1$  Myr) low mass stars (or Young Stellar Objects) present in the cluster at the time ( $t_{\text{SN}}$ ) of the supernova explosion,  $f_{\text{enrichment}}$  is the fraction



of low-mass stars present in the enrichment zone,  $f_{\text{survivors}}$  is the fraction of disks which have survived UV photoevaporation and  $\mathcal{P}_{M_{\text{SN}}}(N_*)$  is the probability that the most massive star in a cluster containing  $N_*$  stars has a mass  $M_{\text{SN}}$ .  $M_l = 8 M_\odot$  and  $M_u = 150 M_\odot$  are, respectively, the masses of the least and most massive star possibly going supernova (Kroupa & Weidner 2005). The dependence of  $f_{\text{YSOs}}$ ,  $f_{\text{enrichment}}$ ,  $f_{\text{survivors}}$  and  $\mathcal{P}_{M_{\text{SN}}}$  on  $N_*$  and  $M_{\text{SN}}$  will be described in the following sections.

#### 4.1. The most massive star in a cluster

Using the Initial Mass Function (IMF),  $dN/dM \propto M^{-(1+\alpha)}$ , where  $N$  is the number of stars and  $M$  the star mass and with  $\alpha = 1.5$  (Scalo 1986), Williams & Gaidos (2007) show that the probability that the most massive star in a cluster containing  $N_*$  stars has a mass  $M_{\text{SN}}$  is:

$$\mathcal{P}_{M_{\text{SN}}}(N_*) = \frac{\alpha f_{\text{SN}} N_*}{[(M_u/M_l)^\alpha - 1] M_u} \left( \frac{M_u}{M_{\text{SN}}} \right)^{1+\alpha} e^{-\mathcal{N}( > M_{\text{SN}})}, \quad (4)$$

where  $f_{\text{SN}} = 0.003$  is the total fraction of stars going supernova, i.e. having a mass larger than  $8 M_\odot$  (Adams & Laughlin 2001).  $\mathcal{N}( > M_{\text{SN}})$ , the number of stars with mass larger than  $M_{\text{SN}}$ , is obtained from the IMF and given by the expression:

$$\mathcal{N}( > M_{\text{SN}}) = f_{\text{SN}} N_* \frac{(M_u/M_{\text{SN}})^\alpha - 1}{(M_u/M_l)^\alpha - 1}. \quad (5)$$

The dependence of  $\mathcal{P}_{M_{\text{SN}}}(N_*)$  on  $N_*$  is shown in Figure 3 for two fiducial masses,  $M_{\text{SN}} = 40 M_\odot$  and  $M_{\text{SN}} = 120 M_\odot$ .

#### 4.2. Fraction of stars in the enrichment zone

Young stellar clusters are segregated in mass, with the more massive stars present at the center of the cluster (Hillenbrand & Hartmann 1998 and references therein). This core-halo structure appears to be primordial, based on morphological (Larson 1982) and dynamical (Hillenbrand & Hartmann 1998) evidence. It is thus reasonable to consider that clusters have a spherical symmetry, and that the massive star responsible for the putative injection of SRs is placed at the center of the cluster (see for example Rho et al. 2006). The number of stars in the enrichment zone is therefore given by the expression:

$$f_{\text{enrichment}}(N_*) = \int_{r_{\text{min}}}^{r_{\text{max}}} \rho(r) 4\pi r^2 dr / \int_0^{R_c(N_*)} \rho(r) 4\pi r^2 dr, \quad (6)$$

where  $\rho(r)$  is the stellar volume density and  $r_{\min}$  and  $r_{\max}$  define respectively the minimum and maximum acceptable distance between the disk and the SN, defining the enrichment zone (see section 2).  $N_*$  and  $R_c(N_*)$  are the number of stars contained in the cluster and the cluster radius, respectively.

Observations of ONC as well as IC348 show that the numbers of stars per unit area, i.e. the internal cluster density distribution, decreases approximately as  $1/r$  (Hillenbrand & Hartmann 1998; Muench et al. 2003), in which case the stellar volume density,  $\rho(r)$ , goes as  $1/r^2$ . Inserting the latter expression into equation (6) yields:

$$f_{\text{enrichment}}(N_*) = \frac{r_{\max} - r_{\min}}{R_c(N_*)}. \quad (7)$$

Using the embedded clusters compilation of Lada & Lada (2003), Adams et al. (2006) find that embedded clusters follow the law  $R_c \approx R_{300} \sqrt{N_*/300}$ , where  $R_c$  is the cluster size and  $R_{300}$  is an empirical parameter varying between 1 and 3 pc (Figure 2 of Adams et al. 2006). This provides an estimate of the average surface density of clusters of different sizes, which can be formulated as:

$$\Sigma = N_*/\pi r_c^2. \quad (8)$$

We consider a wide range for  $\Sigma$  encompassing the range observed by Adams et al. (2006), i.e.  $\Sigma$  varies from 10 to 300 stars/pc<sup>2</sup>. Note that the ONC is characterized by  $\Sigma_{\text{ONC}} = 211$  stars/pc<sup>2</sup>, based on the cluster parameters ( $R_c = 2.06$  pc and  $N_* = 2817$  stars) of Hillenbrand & Hartmann (1998). Inserting equation (8) into equation (7) yields:

$$f_{\text{enrichment}}(N_*) = \frac{(r_{\max} - r_{\min})\sqrt{\pi\Sigma}}{\sqrt{N_*}}. \quad (9)$$

#### 4.3. Fraction of disks surviving photoevaporation

Disks residing within a few tenths of a parsec of a massive O star will be UV photoevaporated on timescales significantly shorter than 1 Myr (e.g. Störzer & Hollenbach 1999). Because disks can have elliptical orbits around the massive star, and because disk-shrinking is limited by the decrease of the mass loss rate with the disk size (Adams et al. 2004), a non-zero fraction of disks might survive nearby massive stars. To estimate the fraction of disks that survive total photoevaporation we will turn again to Orion.

Using the Hubble Space Telescope planetary camera, Johnstone, Hollenbach & Bally (1998) measured the size of 28 protoplanetary disks in the vicinity of  $\theta^1 C$  Ori. Only nine of them have sizes larger than 35 AU, the estimated minimum size of the solar protoplanetary

disk (e.g. Gomes et al. 2005; Hartmann 2005). This means that, in the case of the  $\sim 1$  Myr old ONC, only a disk fraction  $f_{\text{survivors}} = 0.32$  has resisted to photoevaporation and are eligible to SN pollution. This number is compatible with the depletion of disks by a factor of  $\sim 3$  observed by Balog et al. (2007) within 0.5 pc of O stars in the 2-3 Myr NGC 2244 star forming region.

#### 4.4. Fraction of young low-mass stars at time $t_{\text{SN}}$

As discussed in section 2, cosmochemical constraints require the SN injection to occur early in the evolution of the protoplanetary disk. We conservatively estimated that injection had to occur in the first 1 Myr of disk evolution. The fraction of low-mass stars younger than  $\Theta = 1$  Myr at time  $t$  is:

$$\begin{cases} f_{\text{YSO}}(t) = \int_0^t \psi(t') dt' / \int_0^\infty \psi(t') dt' & \text{for } t \leq \Theta \\ f_{\text{YSO}}(t) = \int_{t-\Theta}^t \psi(t') dt' / \int_0^\infty \psi(t') dt' & \text{for } t \geq \Theta \end{cases} \quad (10)$$

where  $\psi(t)$  is the star forming rate.

Star forming rates are not very well constrained and are the subject of debate among astronomers. We therefore consider three different expressions for  $\psi(t)$ , a combination that is likely to bracket reality.

The first expression for  $\psi(t)$  is a step function with a total star formation timescale  $T = 4$  Myr:

$$\begin{cases} \psi(t) = \psi_1 & \text{for } t \leq T \\ \psi(t) = 0 & \text{for } t \geq T \end{cases} \quad (11)$$

Expression (11) gives an overestimated measure of the star formation rate, because star forming regions are known to be more active during their first million years than during subsequent times (e.g. Hartmann, Ballesteros-Paredes & Bergin 2001).

The second expression for  $\psi(t)$  is a linearly decreasing function, terminating on a timescale of  $T = 4$  Myr, due to molecular gas dissipation (Leisawitz, Bash & Thaddeus 1989; Elmegreen 2000; Hartmann, Ballesteros-Paredes & Bergin 2001; Lada & Lada 2003).

$$\begin{cases} \psi(t) = \psi_2 \times (1 - \frac{t}{T}) & \text{for } t \leq T \\ \psi(t) = 0 & \text{for } t \geq T \end{cases} \quad (12)$$

The third expression for  $\psi(t)$  is an exponentially decreasing function with a character-

istic star formation timescale of  $\tau = 0.56$  Myr:

$$\psi(t) = \psi_0 \times e^{-\frac{t}{\tau}} \quad (13)$$

Expression (13) is determined from a fit of star formation rates vs. ages for a suite of observed clusters shown in Figure 4. We emphasize that all the star forming regions considered in this plot have similar sizes (i.e. similar contents of gas). This expression describes a rather extreme, though possible, star formation history with most stars being formed during the first million year of evolution.

Our preferred model corresponds to the linearly decreasing law for  $\psi(t)$  as it describes an intermediary situation between the two extreme cases, the step function and the exponentially decreasing law.

The fraction of low-mass stars (calculated with equation (10)) present in the cluster as a function of time,  $f_{\text{YSO}}(t)$ , is shown in Figure 5 for the three different star formation rates considered. The sharp cut-offs at  $\sim 5$  Myr in Figure 5 for the linear and the step function star formation rates are due to finite duration of star formation in an embedded cluster (Lada & Lada 2003 and references therein). For these cases, there are no low-mass stars young enough to be enriched in the cluster at a time  $t = T + \Theta = 5$  Myr.

For disk contamination to occur, the relevant quantity is the fraction of low-mass stars at the time  $t_{\text{SN}}$  of the supernova explosion, i.e.  $f_{\text{YSO}}(t_{\text{SN}})$ . Evolutionary models for massive stars (Schaller et al. 1992; Romano et al. 2005) provide the time  $t_{\text{SN}}$  at which a massive star goes supernova through the expression:

$$\log(t_{\text{SN}}) = 1.4/(\log M_{\text{SN}})^{1.5}, \quad (14)$$

where  $t_{\text{SN}}$  and  $M_{\text{SN}}$  are expressed in Myr and in solar masses respectively.

#### 4.5. Injection probability in a cluster containing $N_*$ stars: Results

Putting together the expressions defined above, we obtain:

$$P_{\text{SR}}(N_*) = f_{\text{survivors}} \int_{M_l}^{M_u} f_{\text{YSO}}(t_{\text{SN}}) \frac{(r_{\text{max}} - r_{\text{min}}) \sqrt{\pi \Sigma}}{\sqrt{N_*}} \mathcal{P}_{M_{\text{SN}}}(N_*) dM_{\text{SN}}, \quad (15)$$

where  $f_{\text{YSO}}(t_{\text{SN}})$  and  $\mathcal{P}_{M_{\text{SN}}}(N_*)$  are given by equations (10), (14) and (4) respectively. With  $\Sigma = \Sigma_{\text{ONC}} = 211 \text{ stars/pc}^2$  (section 4.2) and  $r_{\text{min}} = 0.1 \text{ pc}$  and  $r_{\text{max}} = 0.4 \text{ pc}$  (section 2), we obtain a set of curves for  $P_{\text{SR}}(N_*)$  shown in Figure 6. Our curves are slightly below that calculated by Williams & Gaidos (2007) because we take explicitly into account the disk

photoevaporation, and because we model the timing of injection in a fashion dictated by the cosmochemical constraints, i.e. we consider that injection happened during the first Myr of disk evolution rather than at any time (section 2).

The probability for SR enrichment peaks at  $\sim 10\,000$  stars. It is however very low as it reaches a maximum value of  $\sim 0.4\%$  for the most favorable case, corresponding to a step function law for the star formation rate  $\psi(t)$ . It peaks at  $\sim 0.03\%$  for the exponential form of the star formation rate, which is based on the data shown in Figure 4. Our preferred model (a linearly decreasing function for  $\psi(t)$ ) gives an intermediary result with a maximum value of  $\sim 0.3\%$ . Increasing  $\Sigma$  to its maximum value,  $\Sigma = 300$  stars/pc<sup>2</sup>, does not substantially change these results, because  $P_{\text{SR}}(N_*)$  varies smoothly with the square root of  $\Sigma$  (see equation (15)) and all our calculations are normalized to the *high* stellar density of the ONC.

#### 4.6. Probability of injection for *any* disk

To calculate the probability of SR injection for *any* protoplanetary disk attached to a low-mass star in the Galaxy,  $\mathcal{P}_{\text{GAL}}$ , we will integrate  $P_{\text{SR}}(N_*)$  over the probability for a star to form in a cluster of size  $N_*$ , which scales as  $1/N_*$  (Elmegreen & Efremov 1997; Adams & Laughlin 2001). In other words,

$$\mathcal{P}_{\text{GAL}} = \mathcal{K} \int_{N_{\text{min}}}^{N_{\text{max}}} P_{\text{SR}}(N_*) \frac{dN_*}{N_*}, \quad (16)$$

where  $N_{\text{min}} = 100$  and  $N_{\text{max}} = 5 \times 10^5$  are the minimal and maximal sizes of stellar clusters respectively (McKee & Williams 1997; Williams & Gaidos 2007). The normalization constant,  $\mathcal{K} = 9.39 \times 10^{-2}$ , is calculated using the observation that  $\sim 80\%$  of stars form in clusters larger than 100 members (Lada & Lada 2003). Figure 7 shows  $\mathcal{P}_{\text{GAL}}$  for the three different star forming rates discussed in section 4.4. In our preferred case, where  $\Sigma = \Sigma_{\text{ONC}} = 211$  stars/pc<sup>2</sup> and  $\psi(t)$  follows a linearly decreasing law, the probability for any disk to receive SRs from a nearby SN at the level observed in the solar system is  $1 \times 10^{-3}$  (grey circle in Figure 7). This probability increases with the square root of  $\Sigma$  as expected from equation (15). In the most favorable case, i.e. adopting a step function for the star formation rate and with  $\Sigma = 300$  stars/pc<sup>2</sup>, the probability for any diskS to receive SRs from a nearby SN at the level observed in the solar system is  $3 \times 10^{-3}$ .

#### 4.7. Multiple supernovae

If the cluster size is large enough, multiple supernovae can occur within the lifetime of the cluster. Stars with mass below  $40 M_{\odot}$  can not contribute to the inventory of SRs because they need too long timescales to evolve (see section 3). Multiple supernovae injection of SRs therefore occur only in clusters large enough to contain at least one star whose mass is larger than  $40 M_{\odot}$ . This condition is satisfied only for clusters containing more than  $N_* = 10^4$  stars (Equation (5) and Figure 8).

To calculate the *maximum* contribution of nearby massive stars to a young protoplanetary disk, we assume that, for clusters containing more than  $N_* = 10^4$  stars, every low-mass star will witness a supernova explosion in its youth ( $\leq 1$  Myr), i.e. that:

$$\int_{M_l}^{M_u} f_{\text{YSO}}(t_{\text{SN}}) \mathcal{P}_{M_{\text{SN}}}(N_*) dM_{\text{SN}} = 1. \quad (17)$$

Introducing this condition in equation (15) yields a stringent upper limit, as this statement is probably true only for the most massive clusters ( $N_* \geq 10^5$ ), where there are enough stars to include tens of supernovae whose progenitors stars have masses larger than  $40 M_{\odot}$ . With this generous permission, we calculate the probability for any young low-mass star protoplanetary disk to be contaminated in SRs by a nearby supernova explosion to be  $6 \times 10^{-3}$  in the most favorable case ( $\psi(t)$  described by a step function and  $\Sigma = 300$  stars/pc<sup>2</sup>).

### 5. Discussion

#### 5.1. Beyond Orion: The Carina Nebula

The probability of a protoplanetary disk to receive SRs from a nearby SN explosion would be higher if one considered a star forming region more massive than the ONC. Such a region would contain more massive stars than the ONC according to the initial mass function (Salpeter 1955). For example, a  $120 M_{\odot}$  star would be ready to go SN and deliver SRs to a nearby disk after only  $\sim 3$  Myr of evolution (Figure 1 and equation (14)). But, 3 Myr after the onset of star formation, the star formation rate has already decreased significantly as can be appreciated in Figure 4. Additionally, extremely massive molecular clouds are rare, at least in the vicinity of the Sun. Within 2 kpc of the Sun, where the number of embedded clusters is large enough to make statistically robust observations, the ONC is the most massive example (Lada & Lada 2003). Finally, a more massive cluster contains more massive stars which are more efficient in dissipating molecular gas by ionization and photo-dissociation (e.g. Bally, Moeckel & Throop 2005). Despite these difficulties, the massive

Carina Nebula star-forming region is now proposed by some authors (e.g. Smith & Brooks 2007), instead of Orion, as a good analog for the astrophysical environment of our solar system formation.

The Carina Nebula (NGC3372) is a star forming region situated at 2.3 kpc from the Sun and containing  $\sim 65$  O stars (Smith 2006).  $\eta$  Carinae, the most massive star contained in the Carina Nebula ( $\geq 100 M_{\odot}$ , Davidson & Humphreys 1997), needs  $\sim 3$  Myr to go supernova (Smith 2006). Since the age of the cluster is  $\sim 3$  Myr, assuming it formed at the beginning of the cluster’s life,  $\eta$  Carinae can go supernova anytime now (Smith 2006). Most of the molecular gas in the vicinity of  $\eta$  Carinae has however been cleared away, creating an extended HII region where star formation is halted (Smith et al. 2000 and Figure 5 of de Graauw et al. 1981).

A few evaporating protoplanetary disks were tentatively detected in the Carina Nebula and await confirmation (Smith, Bally & Morse 2003). From the coordinates given by Smith, Bally & Morse (2003), we calculate that the protoplanetary disk closest to  $\eta$  Carinae lies at a minimum distance of 2.4 pc, a factor of  $\sim 10$  too large compared to the distance needed to inject SRs in sufficient number. In addition, the putative protoplanetary disks detected by Smith, Bally & Morse (2003) are significantly more massive (by a factor of  $\sim 100$ ) than the protoplanetary disks observed in Orion (Johnstone, Hollenbach & Bally 1998), or than the expected solar protoplanetary disk ( $0.013 M_{\odot}$ , Hayashi et al. 1985), suggesting that they belong to young intermediate-mass stars rather than to solar-like stars.

The scarcity of solar-like protoplanetary disks in the vicinity of  $\eta$  Carinae is due to the extreme ionizing power of that star which emits  $Q(H) \sim 10^{50.6}$  ionizing photons per second, which can be compared to the  $Q(H) \sim 10^{49}$  photons per second emitted by  $\theta^1 C$  Ori (O’Dell 2001). It confirms that in the immediate vicinity of very massive stars, protoplanetary disks are extremely rare because (1) those accompanying low-mass stars which formed contemporaneously with massive stars were photoevaporated or formed planets (Throop & Bally 2005) and (2) the efficient gas clearing by winds and UV emission has halted new low-mass star formation.

Triggered star formation in the Carina Nebula occurs in the gas-rich region named South Pillars (Smith & Brooks 2007). Smith & Brooks (2007) argue that young stars in the South Pillars region will be pelted by supernova ejecta containing SRs. While it is true that these young stars will be exposed to the supernova ejecta, the South Pillars lie 20 pc away from  $\eta$  Carinae (Smith et al. 2000), almost two orders of magnitude further away than the distance required to incorporate SRs at the abundance observed in the solar system (see section 2). Massive stars which form now in the South Pillars will need several Myr to explode and deliver SRs to the interstellar medium and therefore suffer from the same

difficulties discussed above.

## 5.2. On our probability estimate

In calculating the different probability estimates for the injection of SRs into a young protoplanetary disk attached to a low-mass star, we made several assumptions and simplifications that we discuss in the following.

### 5.2.1. The enrichment zone

We used a minimum distance between the supernova and the disk,  $r_{\min} = 0.1$  pc, proposed by Ouellette, Desch & Hester (2007) from models simulating the interaction of a 25  $M_{\odot}$  SN with a protoplanetary disk. A more massive star, more likely to achieve that goal, would have a more massive ejecta and therefore a more disruptive effect (through momentum transfer) on the disk (Chevalier 2000). The minimum SN-disk distance we adopted is therefore a lower limit, which turns into an upper limit for  $f_{\text{enrichment}}$  (see equation 3) and therefore into an upper limit for the probability of SR delivery by a nearby SN in a young disk.

The distance  $r$  varies with the square root of the injection efficiency ( $\eta$ ) and with the inverse square root of the initial abundance of short-lived radionuclides ( $M_{\text{SS}}$ ) (equation (2)). The initial abundance of SRs is known within a factor of a few (Gounelle 2006). Therefore, changes in their adopted abundance will not change much the results. In the case of injection into a protoplanetary disk, Ouellette, Desch & Hester (2007) show that the injection efficiency is below 1 % for the gas fraction of the ejecta. Though they suggest that SRs could be injected in the disk in the form of dust grains, it remains to be demonstrated how plausible dust injection is, especially given that SN dust condensation efficiency (defined as the ratio of mass of refractory elements condensed into dust to that of refractory elements in the ejecta) is  $\leq 0.12$  (Sugerman et al. 2006 and references therein). Ercolano et al. (2007) estimate an upper limit as low as  $4 \times 10^{-3}$  for the dust condensation efficiency of supernova SN 1987A. If  $\eta$  is reduced to one order of magnitude in equation (2), it will reduce the maximum acceptable distance by a factor of  $\sqrt{10} \sim 3$ , i.e. from 0.4 pc to  $\sim 0.15$  pc. The maximum distance  $r_{\max}$  calculated in section 2 is therefore a strict upper limit, which turns into an upper limit for  $f_{\text{enrichment}}$  (see equation 3) and, accordingly, for the probability of SR delivery by a nearby SN in a young disk.



### 5.2.2. Disk UV photoevaporation

To estimate the fraction of disks which survived UV photoevaporation ( $f_{\text{survivors}}$ ), we calculated from the data of Johnstone, Bally & Hollenbach (1998) the fraction of disks in Orion which are larger than the minimum inferred original size of the solar protoplanetary disk (35 AU, Gomes et al. 2005). This provides a strong upper limit for  $f_{\text{survivors}}$  for three reasons. First, the ONC is only  $\sim 1$  Myr old and at the time of  $\theta^1 C$  Ori explosion (4 Myr from now) many more disks will have their sizes reduced below 35 AU. Second, this estimate does not include the disks which have already fully evaporated and will not capture any SRs. Third, more massive stars, more likely to deliver SRs, have also larger UV fluxes which will result in a more rapid photoevaporation (Johnstone, Bally & Hollenbach 1998). The fraction of disks that survive UV photoevaporation,  $f_{\text{survivors}}$ , which we used in our calculations is therefore an upper limit, as is accordingly the probability of SR delivery by a nearby SN in a young disk.

### 5.2.3. Temporal coincidence of disks and supernovae in a molecular cloud

In calculating  $f_{\text{YSO}}$ , we considered  $\psi(t)$ , the temporal evolution of the star formation rate, at the global molecular cloud scale, and did *not* take into account the dissipation of molecular gas in the immediate vicinity of the most massive star. This is a simplification as discussed in section 3. Because massive stars create very rapidly after their formation a HII region in which star formation is impossible, star formation in molecular clouds occurs in the outskirts of HII regions, at several parsecs from the massive star (Reach et al. 2004; Balog et al. 2007; Hartmann 2005). In other words, after 2-3 Myr of evolution, the star formation rate,  $\psi(t)$ , in the immediate vicinity ( $\lesssim 2$  pc) of any massive star is virtually zero. By assuming non-zero star formation rates, we definitely calculated a strong upper limit for  $f_{\text{YSO}}$  and therefore for the probability of contamination of a young protoplanetary disk by a nearby supernova.

In calculating  $P_{\text{SR}}(N_*)$  (equation (3)) and  $f_{\text{YSO}}$  (equations (10) and (14)), we implicitly assumed that star formation was coeval in the considered star forming region. In fact, it is only if the most massive stars in a cluster formed in advance relative to low-mass stars that the probability of injection can increase. In such a case, the rapid evolution timescale of protoplanetary disks could be reconciled with the slower evolution timescale of massive stars (Figure 2) and the destructive effect of massive stars would play a less important role.

It is commonly argued that molecular clouds have short lives ( $\sim 4$  Myr) and that star formation within them proceed as soon as the cloud is assembled (e.g. Ballesteros-Paredes

et al. 2007). This implies that the star formation age spread is small (though non zero, e.g. Hartmann 2001). On the other hand Palla & Stalher (2000) have argued that molecular clouds live some tens of Myr and that some stars form in advance compared to the majority of stars. Even if this is correct, it would not solve the timescale problem, because all stars which possibly formed early relative to the majority of stars in the cluster have (at least in the case of the ONC) masses below  $0.3 M_{\odot}$  (Palla et al. 2007). Such stars are far from being massive enough to go SN and deliver SRs to a nearby protoplanetary disk. We note that, in general, high-mass stars are likely to form last in a cluster (Bally et al. 1998; Störzer & Hollenbach 1999; O’Dell 2001; Kroupa & Weidner 2005; Henriksen 1986; Boss & Goswami 2007). This implies again that the probability estimates given in the previous sections are upper limits.

#### 5.2.4. *Multiple supernovae*

The contamination probability in the case of multiple supernovae was explicitly overestimated in assuming (equation (17)) that every low-mass star in the cluster will witness a supernova explosion in its youth ( $T \leq 1$  Myr). The overall contamination probability was also implicitly overestimated by keeping  $f_{\text{enrichment}}$  identical to that calculated in the single supernova case. This is because, in calculating  $f_{\text{enrichment}}$  (section 4.2), we assumed that the most massive star is located at the center of the cluster, where the density of stars is highest. In the case of multiple supernovae, the additional massive stars are located in the cluster periphery (as only the most massive star occupies the cluster center) where low-mass stars are rare, decreasing accordingly  $f_{\text{enrichment}}$ .

Even with those gross approximations, the effect of multiple supernovae is to increase the probability by a factor of only a few. This factor of a few would cancel if the physical effect of many more massive stars were properly taken into account. More massive stars would lead to increased photoevaporation power, clearing very large HII regions where star formation is halted. For example the HII region surrounding  $\eta$  Carinae has an expansion radius of 110 pc (Smith et al. 2000). In addition, the presence of many more massive stars would also increase the probability of close stellar encounters, and therefore planetary disruption (see below). For all these reasons, we will ignore the increase by a factor of a few in the calculated probability due to multiple supernovae.

### 5.2.5. Planetary disruption

A low-mass star born in a large cluster where many massive stars are present can endure close stellar encounters, which have the possibility to disrupt the orbits of planets and small bodies. This was modeled by Adams & Laughlin (2001). They showed that for clusters larger than  $\sim 2500$  members, the cluster density is such that stellar encounters would modify the orbits of the giant planets and the Kuiper Belt. This led Adams & Laughlin (2001) to suggest that the Sun formed in a cluster smaller than a few thousand stars. In doing so, they considered relatively long relaxation timescales for clusters. This was criticized by Hester & Desch (2005). Though small clusters live only up to 10 Myr before disruption, there is a non zero fraction of clusters, corresponding to the most massive ones, which live hundreds of Myr (Lada & Lada 2003), similarly to the lifetimes of the Pleiades. Kroupa et al. (2001) suggested on the basis of a dynamical study that the ONC might become an open cluster similar to the Pleiades, reinforcing the idea that for large clusters the relaxation timescales adopted by Adams & Laughlin (2001) is correct. Because other complications might arise (e.g. Megeath et al. 2007) we did not, however, take explicitly into account the effect of close stellar encounters in our calculations. Neglecting these effects for large clusters implies that the probability of SR delivery by a nearby SN to a young disk, which we calculated above, is an upper limit.

## 6. Implications for the origin of short-lived radionuclides

### 6.1. The origin of short-lived radionuclides

The probability for any protoplanetary disk attached to a young low-mass star to receive SRs from a nearby SN at the level observed in the solar system is  $\sim 1 \times 10^{-3}$  in our preferred case. As shown in section 5.2, this value is a stringent upper limit. Although improbable does not mean impossible, this very low probability suggests that other sources should be considered for explaining the overabundance (compared to the interstellar medium average value) of SRs in the early solar system (Wadhwa et al. 2007). Some of the SRs, such as  $^{26}\text{Al}$ ,  $^{36}\text{Cl}$ ,  $^{41}\text{Ca}$  and  $^{53}\text{Mn}$  can be made by *in situ* irradiation together with  $^7\text{Be}$  and  $^{10}\text{Be}$  (e.g. Gounelle et al. 2006), and therefore do not necessitate further elucidation. Iron-60, on the other hand cannot be made by local irradiation (Lee et al. 1998). It is therefore necessary to find a source of  $^{60}\text{Fe}$ , within a plausible astrophysical context. Besides the nearby supernova scenario, which seems to be unlikely, there are two remaining possibilities for the  $^{60}\text{Fe}$  presence in the solar system: (1) a distant SN or (2) an inherited origin resulting from the contributions of many SN.

A distant supernova (i.e. at a few parsecs from the solar system) was invoked in the past as the source of  $^{60}\text{Fe}$  and other short-lived radionuclides (Cameron & Truran 1977; Cameron et al. 1995). In that context, it was also assumed that the supernova shockwave triggered the collapse of the dense core. This proposition has a number of problems. First, very special conditions are needed to inject short-lived radionuclides in a dense molecular cloud core without disrupting it (e.g. Boss & Vanhala 2000 and references therein). The supernova shockwave needs to impact the core with a fine-tuned velocity of  $\sim 20$  km/s. A higher shockwave velocity would disrupt the dense core, while a slower one would fail to induce collapse and inject radioactivities. Second, injection calculations do not take into account the filamentary nature of molecular clouds, which consist of the fractal juxtaposition of high density clumps and low density interclumps matter (e.g. Rho et al. 2006), but treat the cloud as an homogeneous and dense matter. A supernova shockwave within a molecular cloud will follow the path of less resistance, and will probably avoid the denser regions and instead expand into the interclump matter (Chevalier 1999) delivering very few, if any at all, short-lived radionuclides to molecular cloud cores. Third, though the larger size of a molecular cloud core compared to a protoplanetary disk allows it to collect SRs from a SN ejecta at larger distances (see equation 2), it cannot be much further away than a few pc (Looney, Tobin & Fields 2006), and many of the difficulties described above hold in that case too.

## 6.2. The solar system initial content of $^{60}\text{Fe}$

For some years, a high inferred initial  $^{60}\text{Fe}/^{56}\text{Fe}$  ratio (e.g. Mostefaoui et al. 2005) was considered as a smoking gun for ruling out an inherited origin for  $^{60}\text{Fe}$  (Hester & Desch 2005). The experimental situation has now changed as was recently discussed at the Hawaii meeting on the chronology of meteorites<sup>1</sup>. The maximum solar system  $^{60}\text{Fe}/^{56}\text{Fe}$  initial ratio of  $1 \times 10^{-6}$  (e.g. Wadwha et al. 2007) is probably too high an estimate. Below we give a summary of the various estimates for the initial  $^{60}\text{Fe}/^{56}\text{Fe}$  ratio in the solar system.

Measurements of Ni isotopes in CAIs are challenging because CAIs are rich in Ni nucleosynthetic anomalies, which can blur the effect of  $^{60}\text{Fe}$  decay (Birck 2004). An upper limit on the  $^{60}\text{Fe}/^{56}\text{Fe}$  ratio of  $1.6 \times 10^{-6}$  was given by Birck & Lugmair (1988) for an Allende CAI with a Fe/Ni ratio of  $\sim 20$ . We note that no isochron was reported for this object, and that the authors expressed caution about the  $^{60}\text{Fe}$  decay origin of the small ( $\sim 0.01$  %) anomaly detected. A two point internal isochron for an Allende CAI measured by Quitté et

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<sup>1</sup><http://www.lpi.usra.edu/meetings/metchron2007>

al. (2007) gave a lower limit for the initial  $^{60}\text{Fe}/^{56}\text{Fe}$  ratio of  $3 \times 10^{-7}$ .

Measurements on the silicate portion of chondrules from primitive meteorites, including Semarkona, yield  $^{60}\text{Fe}/^{56}\text{Fe}$  ratios between  $1.7$  and  $3.2 \times 10^{-7}$  (Tachibana et al. 2006; Tachibana et al. 2007), while a measurement from a Semarkona troilite (FeS) gives  $^{60}\text{Fe}/^{56}\text{Fe} \sim 9 \times 10^{-7}$  (Mostefaoui et al. 2005). High  $^{60}\text{Fe}/^{56}\text{Fe}$  initial ratios in troilite can be due to Fe-Ni redistribution in the sulfides during later alteration processes (Guan et al. 2007). It is indeed difficult to understand how troilite would have formed with a higher initial  $^{60}\text{Fe}/^{56}\text{Fe}$  ratio than silicates in chondrules from the same meteorite. If an hypothetic time delay of 1.6 Myr is assumed between the formation of the solar system and the closure of the Fe-Ni system in ordinary chondrites (Connelly et al. 2007), initial  $^{60}\text{Fe}/^{56}\text{Fe}$  ratios between  $3.6$  and  $6.7 \times 10^{-7}$  can be calculated from the measurements of Tachibana et al. (2006) and Tachibana et al. (2007).

Differentiated meteorites add to the complexity of the Fe-Ni system. The absence of  $^{60}\text{Fe}$  evidence in minerals from eucrites and angrites with high Fe/Ni ratios lead Sugiura et al. (2006) to put an upper limit of  $1.5 \times 10^{-7}$  on the initial  $^{60}\text{Fe}/^{56}\text{Fe}$  ratio. Quitté et al. (2006) reported values of  $(1.3 \pm 0.8) \times 10^{-9}$  and  $(8.2 \pm 2.6) \times 10^{-9}$  for the  $^{60}\text{Fe}/^{56}\text{Fe}$  at the time of formation of the angrites Sahara-99555 and d’Orbigny. Combined with Pb-Pb ages of  $\sim 3.3$  and  $\sim 2.6$  Myr after CAIs respectively (Amelin et al. 2006; Amelin 2007), these estimates lead to an upper value for the initial  $^{60}\text{Fe}/^{56}\text{Fe}$  of  $1 \times 10^{-7}$ . The study of the eucrites Chervony Kut and Juvinas lead Shukolyukov & Lugmair (1993) to put an upper limit of  $2 \times 10^{-7}$  for the initial  $^{60}\text{Fe}/^{56}\text{Fe}$  ratio.

Although there is at present no consensus on the initial value of  $^{60}\text{Fe}$  in the early solar system, a low value for the  $^{60}\text{Fe}/^{56}\text{Fe}$  ratio of a few times  $10^{-7}$  seems preferred.

### 6.3. An inherited origin for $^{60}\text{Fe}$

While a high ( $1 \times 10^{-6}$ ) initial  $^{60}\text{Fe}/^{56}\text{Fe}$  ratio could be interpreted as a strong evidence for a nearby SN contamination, revision to a lower initial value ( $^{60}\text{Fe}/^{56}\text{Fe} \sim 3 \times 10^{-7}$ ) changes the outcome because it is compatible with a galactic background origin for  $^{60}\text{Fe}$ .

The present average galactic value of the  $^{26}\text{Al}/^{27}\text{Al}$  ratio has been estimated to be  $8.4 \times 10^{-6}$  (Diehl et al. 2006). Recent measurements of  $\gamma$ -ray lines in the interstellar medium with the Integral satellite have yielded a ratio  $^{60}\text{Fe}/^{26}\text{Al} = 0.148$  (Wang et al. 2007). Using an elemental ratio  $^{27}\text{Al}/^{56}\text{Fe} = 0.109$  (Lodders 2003) gives an average galactic value for the  $^{60}\text{Fe}/^{56}\text{Fe}$  ratio of  $1.4 \times 10^{-7}$ . This latter value is identical to the lower estimates of the early solar system inferred from meteorites (see above). Even if the initial solar system  $^{60}\text{Fe}/^{56}\text{Fe}$

ratio was as high as  $4 \times 10^{-7}$  (e.g. Quitté et al. 2007), fluctuations around the average value could easily explain the presence of  $^{60}\text{Fe}$  due to an inherited origin in the solar system.

It is important to note that this estimate is that of the *present* interstellar medium. It might have been significantly different 4.6 Gyr ago. In addition, this number is averaged on the entire inner Galaxy. Heterogeneities in the  $^{26}\text{Al}$  abundance in the Galaxy (Knödlseider et al. 1999) suggest that both  $^{26}\text{Al}$  and  $^{60}\text{Fe}$  abundances can fluctuate around the average value calculated above. Such calculations show that if the initial solar system  $^{60}\text{Fe}/^{56}\text{Fe}$  ratio was only a few times  $10^{-7}$ , the need for a single supernova vanishes and an inherited origin can account for the  $^{60}\text{Fe}$  found in the early solar system. Though  $^{26}\text{Al}$  decays faster than  $^{60}\text{Fe}$ , an inherited origin cannot be excluded for this radionuclide either<sup>2</sup>.

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<sup>2</sup>The recent claim for a late injection of  $^{60}\text{Fe}$  (Bizzarro et al. 2007) was based on  $^{60}\text{Ni}$  deficits (relative to chondrites) in iron meteorites and pallasites, which failed to be confirmed by other groups (Andrews et al. 2007; Regelous et al. 2007; Dauphas et al. 2008). There is at present no evidence for late injection of iron-60.

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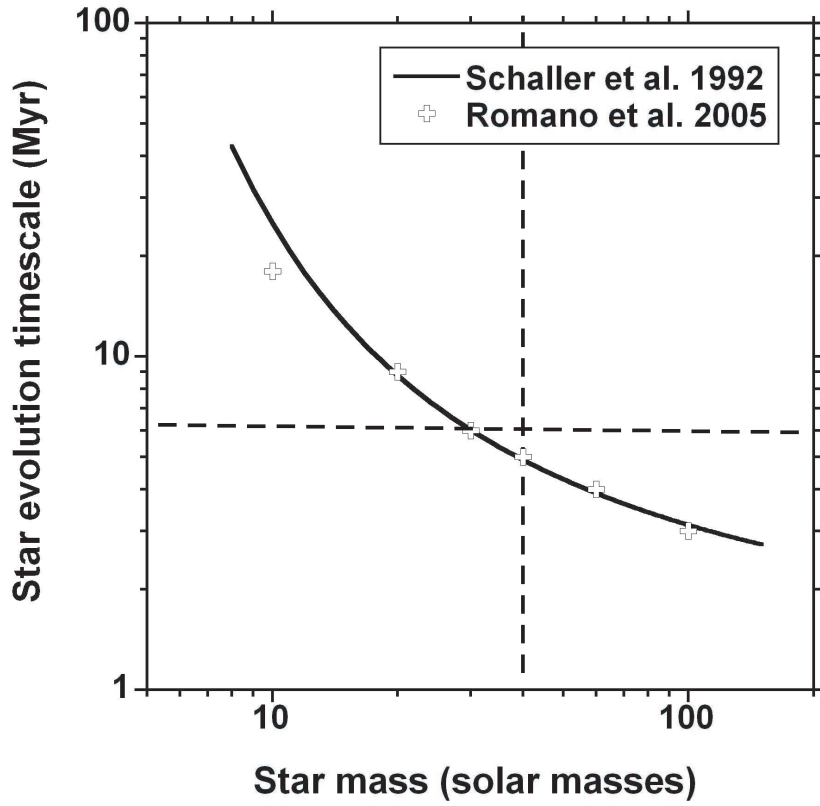


Fig. 1.— Evolutionary timescales of massive stars. Schaller et al. (1992) fitted their models with the expression  $\log(t_{\text{SN}}) = 1.4/(\log M_{\text{SN}})^{1.5}$  where  $t_{\text{SN}}$  and  $M_{\text{SN}}$  are respectively the evolutionary timescale (in Myr) and the mass of the considered star (in  $M_{\odot}$ ). More recent work by Romano et al. (2005) confirm the findings of Schaller et al. (1992).

Fig. 2.— Sketch illustrating the fundamental problems met by the idea of short-lived radionuclides injection in a protoplanetary disk by a nearby supernova. In this cartoon, the evolution of a massive star (large circle) and several low-mass stars within molecular gas (light grey) are shown. In panel (a) is depicted the onset of star formation assumed to be coeval for all stars. During that stage, only dense cores are present. Note that if there is any spread in the onset of star formation, it would correspond to a delayed formation of the massive star (see text). One million year later (panel (b)), the massive star has carved a  $\sim 0.3$  pc wide HII cavity. Disks which are within this cavity are evaporating as depicted by their cometary appearance similar to that observed in Orion protoplanetary disks. Star formation is less vigorous than at  $T = 0$  Myr. At  $T = 2$  Myr (panel (c)), the HII cavity has expanded to  $\sim 1$  pc (see text). The disks which are inside the cavity are totally photoevaporated (Johnstone, Hollenbach & Bally 1998). Low-mass stars that formed at  $T = 0$  Myr now have planets. Very few new stars are forming (see text and Figure 4). When the massive star goes supernova (panel (d)), the stars in the uttermost vicinity of the supernova do *not* have disks, while disks further away have already dissipated to form planets. At this stage, star formation is virtually non-existent because molecular gas has largely been cleaned by the massive star wind and UV emission. A left-over, evanescent, parcel of molecular gas is shown in light grey. Injection of SRs by the supernova in a late-formed disk (marked with an arrow) is an extremely improbable event. An indicative scale would be given by the size (few tenths of parsec) of the HII cavity in panel (b).

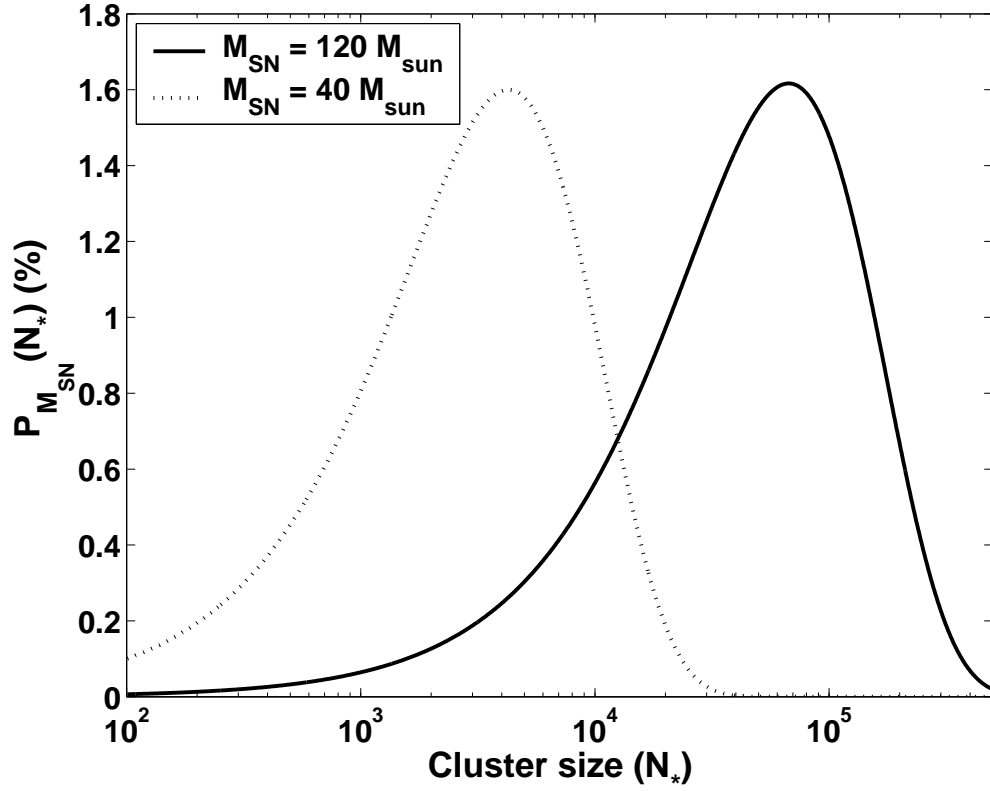


Fig. 3.— Probability that the most massive star in a cluster containing  $N_*$  stars has a mass  $M_{SN} = 40 M_{\odot}$  and  $M_{SN} = 120 M_{\odot}$  (equation (4)). Note that the maximum probability for a  $40 M_{\odot}$  star to be the most massive star occurs for a cluster of  $\sim 4000$  stars, slightly larger than the ONC.

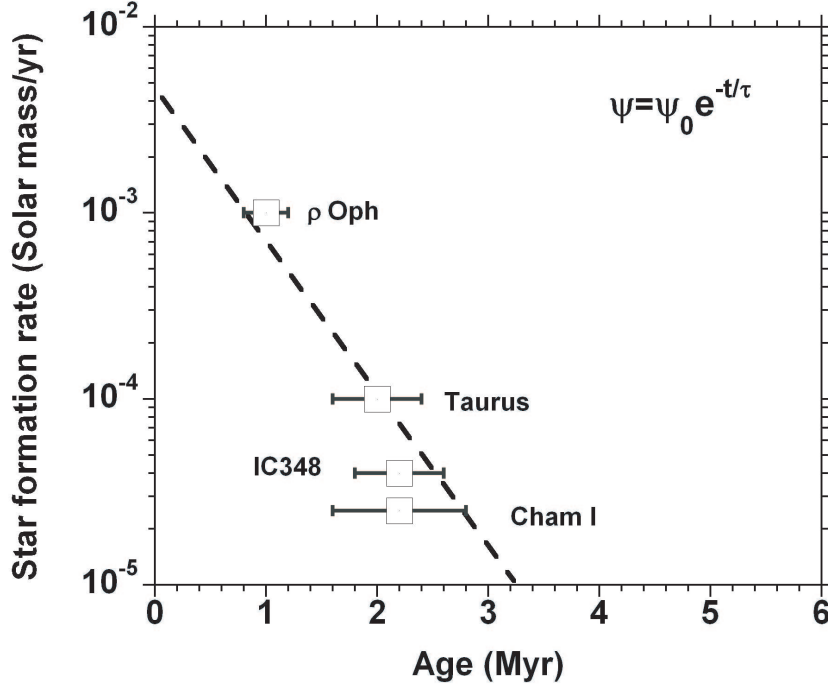


Fig. 4.— Star-formation rate versus age for a suite of well studied molecular clouds. Cham and  $\rho$  Oph stand for Chamaeleon I and  $\rho$  Ophiuchi respectively. The thick dashed line is the fit of the data which minimizes the exponential decrease of the star formation rate (see section 4.4). It gives a decay time constant of  $\tau = 0.56$  Myr. The age of a given star-forming region depends on the mass of the stars and their position on the Hertzsprung-Russell diagram, among other parameters (Palla & Stahler 2000; Hartmann 2001). For  $\rho$  Ophiuchi, we take the commonly accepted age of  $\sim 1$  Myr (Preibich & Zinnecker 1999; Palla & Stahler 2000). For other molecular clouds, we adopt the age compilation as well as their associated error bars given by Haisch, Lada & Lada (2001). These ages are compatible with other, more recent, estimates in the literature (e.g. Luhman 2004; Muench et al. 2007). The errors take into account the error in the mean of the source age derived from a given set of Pre Main Sequence (PMS) tracks (Haisch, Lada & Lada 2001). Errors due to the use of different PMS models are of the order of 1 Myr and could result in a shift of the data without changing the relative age sequence (Haisch, Lada & Lada 2001). Star formation rates for individual molecular clouds are given by Preibisch & Zinnecker (1999) without associated error bars. Note that star formation rates are not available for older clusters because there are no observed star-forming molecular clouds older than a few Myr (Elmegreen 2000; Lada & Lada 2003; Hartmann, Ballesteros-Paredes & Bergin 2001).



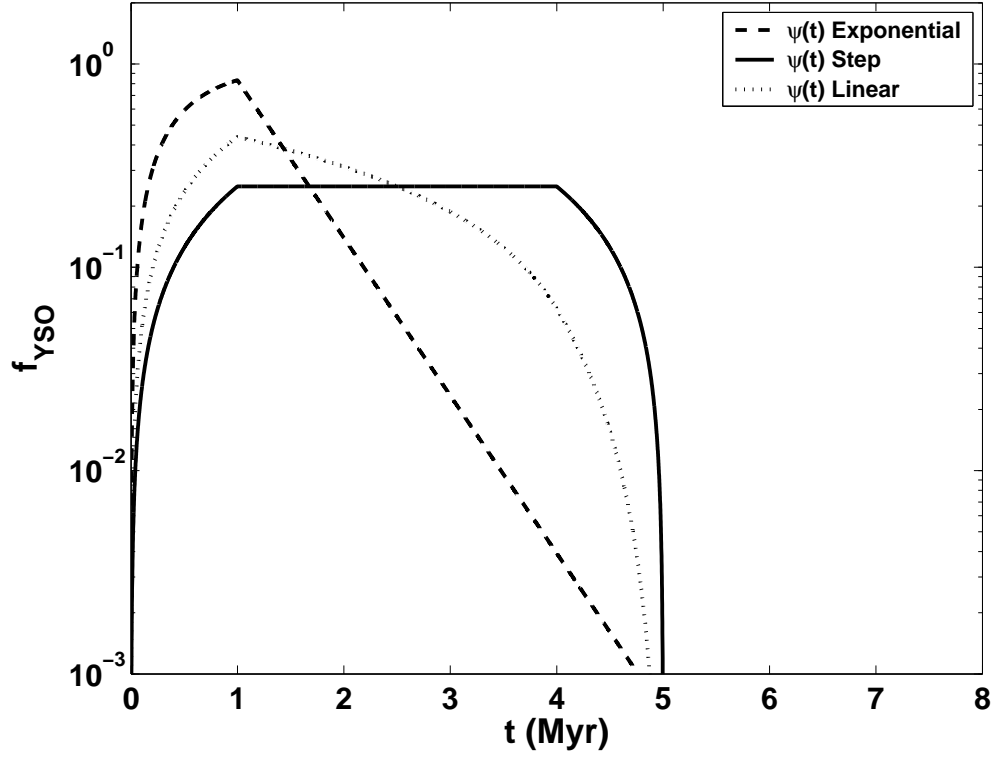


Fig. 5.— Fraction of low-mass stars younger than 1 Myr ( $f_{\text{YSO}}$ ) present in the cluster as a function of time  $t$  (equation 10).  $f_{\text{YSO}}$  is shown for the 3 expressions considered for the star forming rate,  $\psi(t)$ , and discussed in the text.

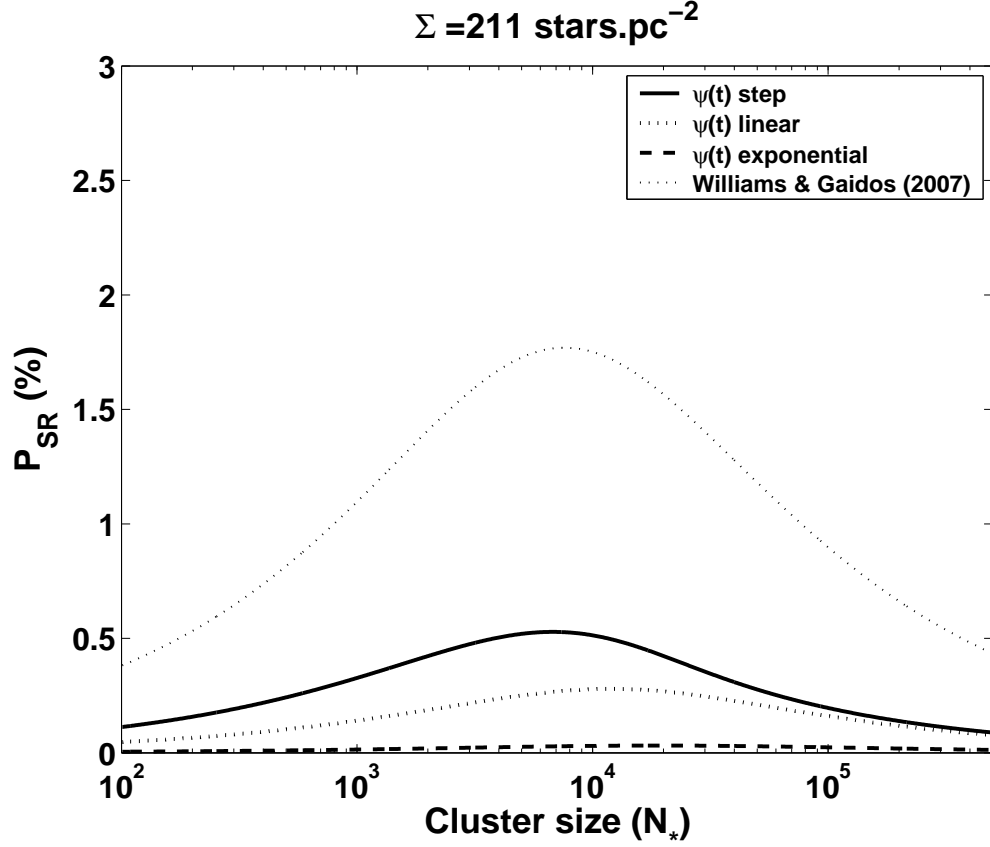


Fig. 6.— Probability of protoplanetary disk enrichment in SRs at the level observed in the solar system ( $P_{\text{SR}}(N_*)$ ) as a function of the cluster size ( $N_*$ ), and calculated for the different expressions of the star forming rate  $\psi(t)$ . The curves were obtained using the ONC stellar surface density of  $\Sigma_{\text{ONC}} = 211 \text{ stars/pc}^2$ . A similar curve obtained by Williams & Gaidos (2007) is shown for comparison (with  $\Sigma_3 = 211 \text{ stars/pc}^2$ ).

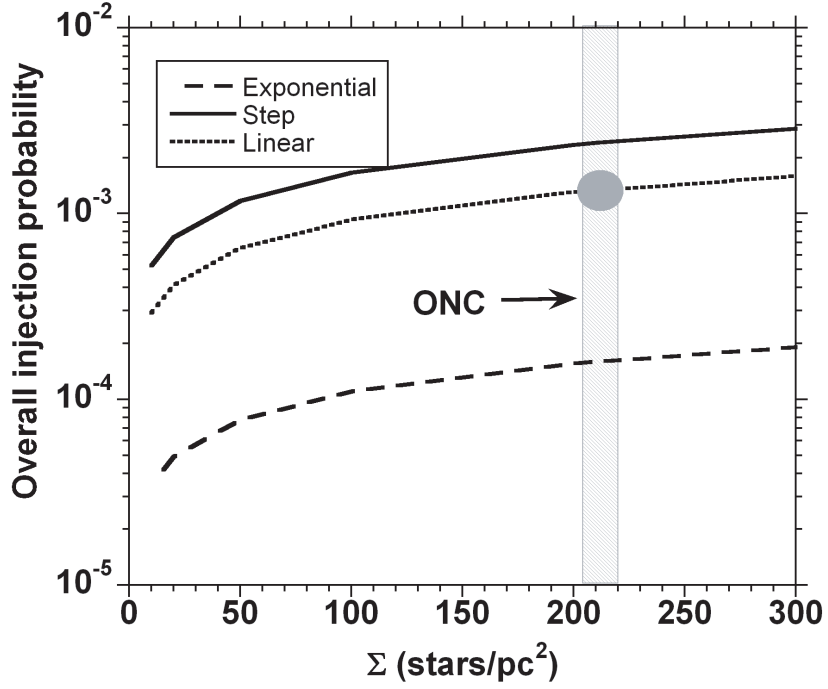


Fig. 7.— Probability for *any* protoplanetary disk attached to a young low-mass star to receive SRs from a nearby SN at the level observed in the solar system. The vertical line denotes the surface density of the ONC, while the grey circle represents our preferred model, with the Orion surface density and a linear decrease of  $\psi(t)$ .

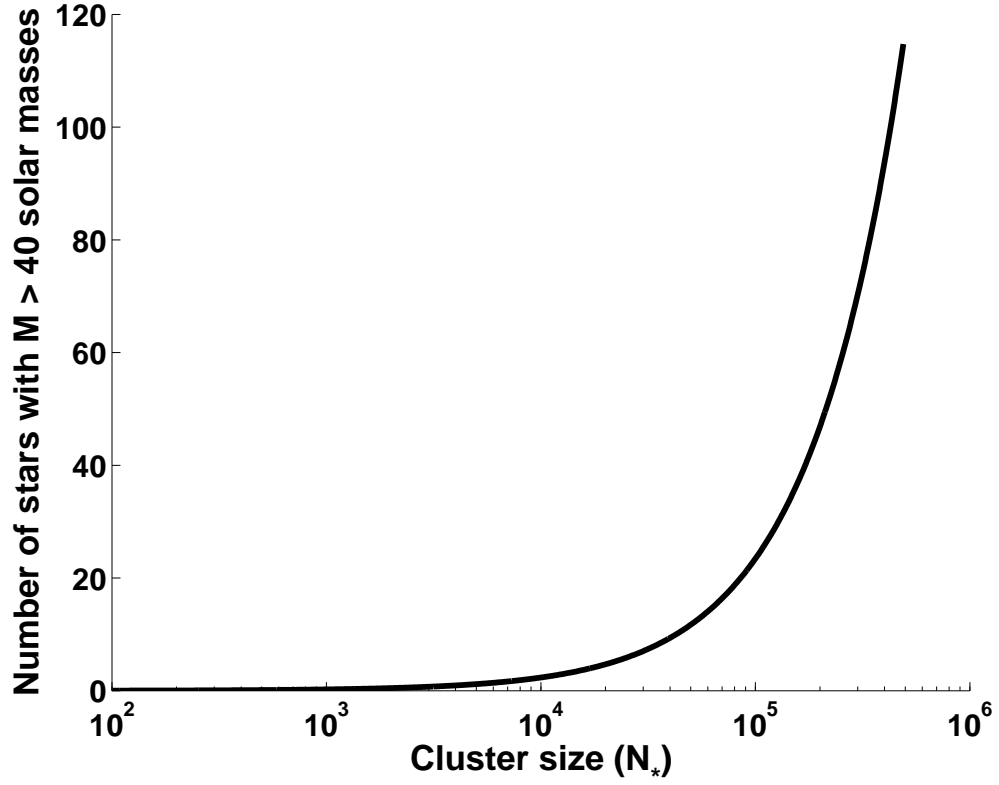


Fig. 8.— Number of stars with mass larger than  $40 M_\odot$  as a function of cluster size (calculated from equation (5)). Multiple supernovae ( $\geq 2$ ) capable to inject SRs in a cluster occur only in clusters containing more than  $10^4$  stars.